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13. ABSTRACT *(Maximum 200 words)*

Emerging military communication systems are being developed to provide multimedia communication on the move. To this end it is critical that the network maintain a deterministic type of service across an interconnected mobile environment. In these environments the provision of highly available and reliable communication with a guaranteed Quality of Service must overcome the problems of interference and potentially frequent topology reconfiguration. In this proposal we developed and validated a number of approaches that provide bonded delay and guaranteed delivery of data in rapidly moving mobile networks and lay the basis for future integration of additional services in the same network. Our solutions cover the access level and the network level protocols and support an easy integration with terrestrial networks by being in many ways consistent with the emerging ATM standard.

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1 Statement of the Problem Studied

The central studied problem was, as described in details in the proposal, the provision of routing with guaranteed bounded delay in tactical radio networks for data communication.

The motivation of this investigation was derived from the fact that the design of network protocols in military communication environments must account for the unique and stringent performance requirements of the military applications. Many of these applications are pertinent to the distribution of acquired intelligence, to command and control and require a reliable and timely transport mechanism.

To deal with the need for reliability, availability and response for time critical data, military communication has traditionally been oriented towards protocols with deterministic service, such as that found inSS/TDMA control of satellite links, or T1, T2, T3 ground relay optic fibers. This trend for deterministic service in military communication is certain to continue also in the future.

To maintain a deterministic type of service across an interconnected military environment, all network segments composing the network interconnect must guarantee the same level of service quality. In this respect mobile radio networks have traditionally been a "weak" link in the network interconnect. The main reason for this situation lies in the fact that in radio networks the provision of high availability and reliability must overcome the problems of interference and potentially frequent topology reconfiguration related to network mobility.

In this proposal we developed and validatesd a number of approaches that provide bonded delay and guaranteed delivery of data also in mobile networks and lay the basis for future integration of additional services in the same network.

2 Summary of the Most Important Results

It became clear in the investigations that reliable end-to-end bounded delay routing in a mobile network has to be built on a specially designed media access layer wich also guarantees deterministic operation. This, combined with appropriate congestion control, serve as the basis on top of which a deterministic service network layer protocols can be built.

Accordingly, to support reliable bounded delay routing, the first part of our investigation was dedicted to novel media access protocols, and congestion control algorithms for radio networks. On top of these, a new network layer protocol with bounded time delivery was developed. Appropiate simulation software was also developed for algorithm testing and simulation of the proposed protocols and for the performance evaluation of the resulting network operation.

In the following four subsections the main results are overviewed in the four areas mentioned above:

1. Media access protocols
2. Congestion control
3. Routing
4. Simulation and performance evaluation

2.1 Media Access Protocols

Transmissions scheduling is a key design problem in packet radio networks, relevant to TDMA and CDMA systems. A large number of topology dependent scheduling algorithms are available, in which changes of topology inevitably require recomputation of transmission schedules. The need for constant adaptation of schedules to mobile topologies entails significant, sometime insurmountable, problems. These are the protocol overhead due to schedule recomputation, performance penalty due to suspension of transmissions during schedule reorganization, exchange of control messages and new

schedule broadcast. Furthermore, if topology changes faster than the rate at which new schedules can be recomputed and distributed, the network can suffer a catastrophic failure.

To solve these problems, the paper [3] proposes a substantially different way of scheduling. Its objective is to make the schedules *independent of the detailed topology.* Instead, the schedule depends only on *global* network parameters, namely, the number of nodes and the maximum degree (number of neighbors) a node can have, while still guaranteeing the fundamental properties of scheduled access.

The protocol is unique in providing a *topology transparent* solution to scheduled access in multi-hop mobile radio networks. The proposed solution adds the main advantages of random access protocols to scheduled access. Similarly to random access it is robust in presence of mobile nodes. Unlike random access, however, it does not suffer from inherent instability, and performance deterioration due to packet collisions. Unlike current scheduled access protocols, the transmission schedules are independent of topology changes, and, additionally, channel access is inherently fair and traffic adaptive.

Different versions of the protocol, optimized according to different usage goals, are presented in [1], [3], [5], [8]. Each of them guarantees *deterministically bounded delay* on the data-link layer, despite the randomly changing network topology.

The media access problem in the case when users can receive packets on more than one common channel is investigated in [2], [7]. For this type of systems, a new channel access protocol is presented. It is proven that under heavy homogeneous load the protocol guarantees the *maximum achievable throughput among all possible protocols.* The general model can be applied to different systems, according to various realizations of the logical channels. For example, in packet radio networks the channels can be realized by different carrier frequencies (FDMA) or by different codes (CDMA) etc. The simplicity and optimality of the protocol make it attractive for practical applications.

In CDMA networks the usage of orthogonal codes makes technically possible to receive more than one packets successfully in any given time

slot. Scheduling of transmissions in networks with *multiple reception capacity* raises new problems for the media access protocol. The paper [4] presents the first known algorithm that works for arbitrary value of the reception capacity. (A technical report version is found in [6]). It is proven in [4] that the achieved framelenght is within a small factor of the optimum.

2.2 Congestion Control

Congestion control is an important part of the lower layer protocol hierarchy, necessary to support reliable end-to-end service. In particular, bounding the queueing delay is an important component of providing bounded delay end-to-end service.

To provide a simple, efficient and reliable solution, a new congestion control strategy was presented in [9], targeted towards integrated services in networks with time-slotted access, as in for instance in ATM networks. The proposed control combines a new transmission control scheme with access control to provide efficient, fair, and congestion free network control. The transmission control scheme uses counters at each node to regulate the flow of packets from the output packet queues to the outgoing link. The transmission control is designed to be flexible in accommodating various existing and expected applications and to be simple in implementation. The resulting congestion control strategy supports different service rate for each service class according to its individual requirements and meets the GoS of each service class. The strategy is proven to provide *bounded end-to-end queueing delay* for each individual real-time application and at the same time gives a best effort service to loss-sensitive and delay-tolerable data streams.

The strategy termed *Counter Based Control* (*CBC*) strategy has the goal of flexibly dealing with applications that have various characteristics and requirements and providing guaranteed GoS for each service class. It is based on two principles. The first principle of *CBC* is the assignment of bandwidth to each connection according to its bandwidth demands, independently of other existing connections. In this way each service class can be assigned exactly the bandwidth required, and new classes can be added easily without interrupting the network operation. The second principle of *CBC* is main-

taining the packet stream pattern of each real-time connection as close as possible to its pattern at the source node throughout the network.

2.3 Routing

Several results were achieved concerning the various aspects of routing, see [10], [11], [12], [13], [14].

The paper [14] deals with optimizing the system of *virtual paths* in large networks. The virtual path concept has been also been shown to be a powerful transport mechanism for ATM networks. By allowing a group of virtual circuits (individual connections) to be switched together it leads to a significantly better use of network resources. The paper presents a three-phase optimization procedure for establishing virtual paths. It is shown that each phase requires the solution of computationally hard (NP-complete) algorithmic problems and, therefore, approximate solutions were developed. The solutions to all phases have feasible computational complexity for even very large networks. Furthermore, the proposed approach was shown to yield guaranteed performance, and provable bounds on the deviation of the results from the optimum.

The paper [10] deals with the optimization of the virtual paths system from a bandwidth utilization perspective. While previous research on VP management has basically assumed that bandwidth is unlimitted, as often assumed in ATM networks, in wireless networks bandwidth is always at a premium. The solution [10] presents an efficient algorithm that finds a system of VP routes for a given set of VP terminators and VP capacity demands. This solution is motivated by the need to minimize the load, or reduce congestion, generated by the VP's on individual links. A nontrivial performance guarantee is proven for the quality of the proposed solution and numerical results show that the proposed solution carries the potential for a near optimal allocation of VP's.

Various aspects of bounded delay routing are explored in [13] and [11].

[13] presents bounds on the queueing delay of shortest path routing operating under path-assigned priorities. The situation is investigated when

different packets can delay each other as they meet at nodes while proceeding on distinct routes. It is proven that, although the packets can meet several times on their routes, nevertheless, the delay performance can be isochronously mapped into the simpler situation when any two packets meet at most once on their way.

In [11] the connection between routing and transmission scheduling in radio networks was investigated. In a CDMA/TDMA data-link protocol of radio networks collision free transmission schedules are created using a cyclic, time oriented scheduling of transmissions. Transmission scheduling has so far been considered in the context of data link control as a means to maximize spatial reuse of the available bandwidth and to optimize link capacity allocation according to traffic requirements. In the paper it is shown how routing considerations can be incorporated in determining data-link schedules allowing the use of shortest paths while avoiding congestion on heavily occupied links. This results in reduced end-to-end delays and increased network capacity in radio networks. A new approach is introduced which allows the performance of such networks to be derived analytically, using recursion relations. The approximate solution provides a tractable way for analyzing general topology radio networks with finite buffers, using fixed routes and arbitrary datalink schedules.

The problem of routing is approached from the viewpoint of more complex *virtual subnetworks* in [12]. Virtual subnetworks are expected to play an important role in high speed integrated multirate networks that carry mutimedia traffic and provide a wide scale of sophisticated services.

2.4 Simulation and Performance Evaluation

The numerous algorithms developed within the project have been tested numerically and with simulation. Appropiate simulation software was developed for algorithm testing, and for simulating performance of proposed protocols and the mobile network. The results of numerical evaluation and simulation are presented in details in the respective referenced papers.

Beyond the various protocol-specific programs and software tools the development of a useful general software tool was reported in [15]. With the

advent of formal specification languages, it has become possible to represent complex communication protocols formally and unambiguously. Presence of automated tools for protocol specification and verification has made inroads for the wide-spread use of formal languages. One of the often neglected issues in protocol development activities centered around formal languages is the performance efficiency of the protocol under given network implementation. Many performance simulation tools are available, but they either do not use standard formal languages for protocol specification or lack a comprehensive performance prediction capability. The paper [15] presents a software tool which unifies formal protocol specification and performance prediction and thus enables protocols specified in FDT Estelle to be simulated for performance on a given network configuration which include point-to-point networks, common bus Ethernet, ring and multihop static and mobile packet radio networks. It allows fine tuning of an otherwise correct protocol to improve its efficiency without the actual implementation and thus it helps in building rapid and efficient prototypes.

3 List of Participating Scientific Personnel

H. Zhang: Expected to graduate (Ph.D.) in 1995.

Eric Wong: Graduate (Ph.D.) 1994.

H. Y. Ahn: Graduated (Ph.D.) 1994.

A. Fumagalli: Graduated (Ph.D.) 1993.

G. Hegde: Graduated (M.Sc.) 1993.

K. Satam: Graduate (M.Sc.) 1992.

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